ORBITAL WELDING OF SMALL-BORE SUPER DUPLEX TUBE USING GTAW FLUX

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ABSTRACT

Manual gas tungsten arc welding (GTAW) historically has been used to join small-bore Super Duplex SAF 2507™ tubing. Increasing emphasis on cost reduction and improved quality over the life of a project (life-cycle costing) has led to the development of alternate, more productive methods to join small-bore tubing. The purpose of the present investigation is to evaluate the benefits and limitations of using a penetration-enhancing flux along with automatic orbital GTAW equipment.

Single pass autogenous orbital welding procedures were developed to produce full fusion square butt joints in SAF 2507 tubing with diameters ranging from 6.35 mm to 12.7 mm (0.25 to 0.50 in.) and wall thickness ranging from 0.89 mm to 2.41 mm (0.035 to 0.095 in.). Weld metal microstructure, mechanical properties, and corrosion resistance were evaluated. The results of this study demonstrate that it is possible to consistently maintain a duplex microstructure with 40 to 50 % ferrite without the use of filler material or nitrogen additions to the shielding gas. The tensile properties and corrosion resistance (ASTM G150 and G48 Method A) were commensurate with tensile properties and corrosion resistance of multiple pass welds made with high nickel filler and nitrogen shielding gas.

Field application trials using orbital GTAW equipment and GTAW flux for small diameter heavy wall tubes were conducted. The results of the application trials demonstrate that defect rates (relative to manual multipass procedures) were reduced from ~40 to < 2 % by using an automatic welding system and GTAW flux. The time required for fit up and welding of a typical tube joint was also reduced from approximately 20 minutes for a manual weld to less than 5 minutes.

KEY WORDS

GTAW Flux, Duplex, Super Duplex, Orbital Welding, SAF 2507, Stainless Steel

INTRODUCTION

The gas tungsten arc welding process is used to produce high-quality welds in a wide variety of materials. Applications include welding of sheet, plate, pipe, tube, and castings for use in aerospace, semiconductor, power generation, shipbuilding, and other industries. Advantages of using the GTAW process include high-quality weld deposits, precise control of welding parameters, and low equipment costs. The GTAW process is widely used in industry for single-pass welds and the root passes of multipass welds. Autogenous orbital GTAW, an "automatic" iteration of manual GTAW, is a widely accepted method for creating repeatable, clean, high-quality, and documented welded connections of conventional stainless steel tubing and pipe, such as 316L.

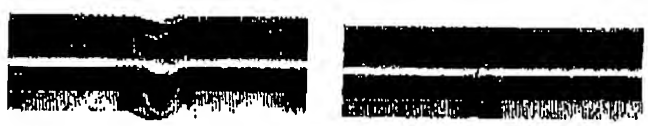

Figure 1: 12.7mm x 2.41mm autogenous weld a.) without the use of flux b.) with Swagelok Flux

Despite its broad use, autogenous orbital welding has had only minimal acceptance for welding duplex and super duplex steels. This was primarily due to a series of technical challenges: 1) Weld penetration can be difficult to manage, resulting in welds that are undesirably wide on the tube surface and narrow on the tube interior. 2) Weld heat inputs tend to be relatively high and often require multipass weld schedules. 3) Control of the weld bead can be difficult, leading to sagging or saddled appearance in the weld profile and a possible reduction in strength or wall thickness (see Figure 1a). 4) Weld gas selection and use can be complicated, resulting in multiple Weld Procedure Specifications (WPS) for different wall thicknesses of the same material.

A flux has been developed for use with the gas tungsten arc welding (GTAW) process that increases penetration by as much as 300 percent compared to non-flux practices. GTAW flux is a mixture of inorganic material suspended in a volatile media or a binder. The mixture typically is applied to the top surface of the joint, in a layer less than 0.127 mm (0.005 in.) thick, prior to welding. The volatile liquid is allowed to evaporate, and the weld is then produced. Standard GTAW equipment and consumables are used (Figure 2), including shielding and backing gases. The flux is not intended to

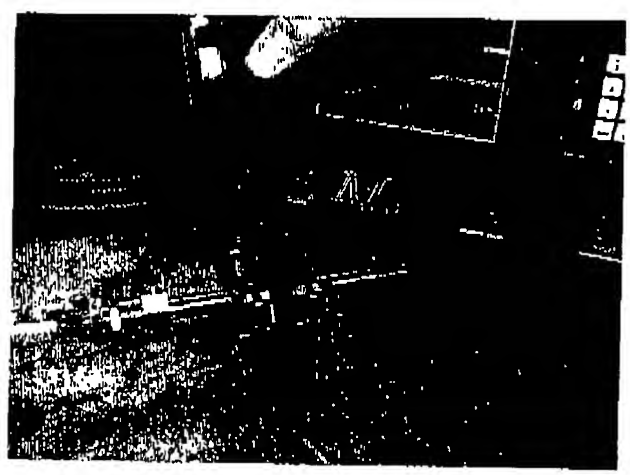

Figure 2: 12.7mm x 2.41 mm SAF 2507 butt weld, Illustrated in a typical weld configuration using the Swagelok M100 power supply, series 5 weld head and fixture block.

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provide shielding for either the face or the root of the weld.

While GTAW flux for austenitic stainless steel, nickel bas alloys, and titanium alloys has been the subject of recent investigations[1-6], published studies reporting the use of GTAW flux for duplex and super duplex stainless steel applications has been limited. When compared to welding of austenitic stainless steel, welding of duplex and super duplex stainless steels requires that the composition of the weld and weld cooling rates be carefully controlled to maintain an adequate balance of austenite and ferrite in the weld and heat affected zone (HAZ).

When SAF 2507 is welded, a fully ferritic solidification mode is observed. During subsequent cooling, heterogeneous nucleation of austenite occurs. The growth rate of austenite depends on the cooling rate and chemical composition of the weld. For optimal toughness and corrosion resistance in super duplex stainless steels, it is desirable to develop procedures that result in a weld containing approximately 40-50 volume percent ferrite. Additional complications can be encountered during GTAW welding of duplex and super duplex tubing for a number of reasons. First, sulfur is typically maintained at levels of less than 0.006 wt. pct. (60 ppm). Low sulfur concentrations make it difficult to establish and maintain consistent penetration in thicker materials without using high arc energies. Thus, it becomes increasingly difficult to control acceptable weld bead profile and phase balance while avoiding intermetallic formation in duplex and super duplex stainless steel. Second, shielding gas selection can be complicated with multiple argon/nitrogen combinations (to maintain austenite) and/or helium additions (to increase penetration).

The objective of this study was to evaluate the use of GTAW flux and orbital welding equipment to join small-bore super duplex tubing. Following development of appropriate procedures and verification of mechanical properties, field application trials were conducted.

CUSTOMER ACCEPTANCE CRITERIA

Customer requirements for welds on SAF 2507 tubing for sub-sea applications were reviewed and are summarized as follows:

- Pass minimum transverse tensile (UTS>914 Mpa-132 ksi), bend, weld geometry, and hardness requirements (32 HRc max.) as specified in ASME Section IX
- Pass X-ray with no defects at <2 % sensitivity
- Pass ASTM G48, Method A corrosive weight loss test with no visual signs of pitting at 20x magnification and < 1g/m^2 weight loss
- Maintain a Critical Pitting Temperature (CPT) of > 55°C (131°F) for weld metal and 80 °C (176°F) for base metal of the test samples in ASTM G150 (NaCl solution) test
- Verify absence of Sigma and other intermetallic phases in weld and HAZ wh n examined at 400x magnification
- Maintain ferrite content of 35 to 65 %
- Demonstrate process repeatability and improved productivity

Table 1: Suggested allowable working pressur s for SAF 2507 welded connections

Tube OD, mm (in.)	Tube wall, mm (in.) bar (psig)				
	.89 (.035)	1.24 (.049)	1.65 (.065)	2.11 (.083)	2.41 (.095)
6.35 (1/4)	875 (12 700)		1902 (27 600)		
9.53 (3/8)	(551) 8 000		1123 (12 400)	1523 (22 100)	
12.7 (1/2)	427 (6 200)	620 (9000)	854 (12 400)		1378 (20 000)

Note: Testing was performed on fully annealed SAF 2507 tubing, ASTM B789, for metal temperatures from -20° to 100°F (-29° to 37°C). Allowable working pressures calculated from S values (53 300 psi), ANSI B31.3 Chapter IX.

EXPERIMENTAL PROCEDURE

Welds were produced on the tube dimensions summarized in Table 1. Autogenous orbital welds were produced using a GTAW flux with chemistry requirements controlled by Swagelok. The flux composition falls within the SS-7 flux patent held by EWI (see Ref. 2). Welding and procedure variables are summarized in Tables 2 and 3. The use of GTAW flux allowed full penetration to be maintained with substantially reduced arc energy (about half) compared to typical non-flux practices.

Table 2: Summary of Welding Variables Utilized to Produce Experimental Welds

Variable	Type
Flux	SWS-Flux-1
Carrier	Acetone
Application	Brush
Material	SAF 2507
Joint Preparation	Square butt
Power Supply	Swagelok M100
Weld Head	Swagelok Series 5
Electrode	Tungsten-2%Th & 2% Ce
Electrode Angle	19-22
Arc Length (mm)	1.14
I.D. Gas	Argon
O.D. Gas	Argon

Table 3: Summary f W lding Parameters Utilized to Produce Experimental Welds

OD (mm)	Wall (mm)	Travel Speed (mm/min.)	Average Voltage (volts)	Average Current (amps)	Arc Energy (kJ/mm)
6.35	0.89	57.9	9.0	18.75	0.18
6.35	1.65	57.9	9.0	35.25	0.33
9.53	0.89	71.8	8.8	22.75	0.17
9.53	1.65	71.8	8.8	33.13	0.24
9.53	1.80	71.8	8.8	36.13	0.27
9.53	2.11	71.8	8.8	46.63	0.34
12.70	0.89	163.6	9.6	28.75	0.10
12.70	1.24	152.4	9.6	32.75	0.12
12.70	2.41	53.5	9.6	45.00	0.48
12.70[1]	2.41	53.5	9.6	47.28	0.51
12.70	2.41	69.7	9.7	69.7	0.24

[1] Denotes weld schedule using cerlated electrodes.

A typical chemical analysis of the SAF 2507 material is given in Table 4. Chemical analysis was performed using inductively coupled plasma (ICP) methods and various LECO interstitial analyzers. Ferrite was characterized optically and using both a magnegage and Fischer ferritscope. Welds were examined at 400 and 1000x magnification. Weld tensile, bend, and contour properties were determined according to specifications given in ASME Section IX [QW-462.1, QW-462.3, QW-302.4], Ref. 7.

Table 4: Compositional Requirements of SAF 2507 Material Compared to Base Metal and Weld Metal Average

	C max.	Si max.	Mn max.	P max.	S max.	Cr	Ni	Mo	N	Ti	O
Nominal	0.030	0.8	1.2	0.035	0.02	25	7	4	0.30	NL	NL
Base Metal (average)	0.015	0.30	0.45	0.019	0.001	24.86	6.95	3.79	0.29	0.005	0.008
Flux Weld (typical)	0.025	NT	NT	NT	0.002	NT	NT	NT	0.29	0.013	0.024

Note:This material is a patented and trademarked material of Sandvik Steel-AB. NL=Not Listed, NT=Not Tested

Corrosion testing was conducted in accordance with ASTM G48 and ASTM G150. Corrosive weight loss (based on ASTM G48 Method A[8]) was used as a go/no go test for the corrosion resistance of the SAF 2507 weldments. Samples tested by Method A were immersed in 6 % $FeCl_3$ for a period of 24 hours with the temperature held at 40°C. The weldment was considered unacceptable if the weight loss after immersion was in excess of 1g/m^2. The samples for this test were cut in lengths that were 7 times the width of the weld; the weld was located in the center of the sample. Both the ID and the OD of each sample were tested.

Electrochemical CPT testing (based on ASTM G150[9]) was performed to determine resistance to localized (pitting) corrosion. The method differed from ASTM G150 in that a stir bar was used in place of nitrogen gas for agitation. The electrolyte was [illegible] chemicals and DI water. An immersible

magnetic stirring plate and bar placed at the bottom of the beaker was used to reduce temperature gradients within the cell. The sample was placed in solution to equilibrate for 10 min. at 0 °C (32 °F). Following the initial delay, a potential of 700 mV_{SCE} was applied to the sample while the temperature was ramped at 1°C per minute. Current was monitored continuously. The test was ended when the current density exceeded 100 µA/cm^2 for 60 s, which signified the onset of localized (pitting) corrosion. The sample was then removed from the cell and rinsed in de-ionized water. All samples were examined to identify the location of the pitting and to inspect for under-lacquer corrosion. Any samples that showed signs of under-lacquer corrosion were discarded. A minimum of five samples were tested for each condition.

Welding procedures and equipment utilized in the laboratory tests were transferred to field welding personnel at three test site locations. The welding was conducted using the following tube sizes: 6.35 mm x 1.65mm (0.25 x 0.065 in.), 9.52 mm x 1.80 mm (0.375 x 0.083 in.) and 12.7 mm x 2.41 mm (0.50 x 0.095 in.). Training of welders took approximately 3 working days. Properties of selected field welds were analyzed using the methods discussed above.

RESULTS AND DISCUSSION

The results were consistent with previous studies using GTAW flux. Using lower arc energies than without flux, complete penetration in the SAF 2507 tubing was achieved while maintaining an acceptable fusion zone profile.

Figure 3: Images above were taken using one heat (HN 446518) of SAF 2507 tubing-12.7mm x 2.41mm. Weld bead profile coupons were produced using the following procedures: a.) weld completed using GTAW flux with an Arc Energy of 0.24 kJ/mm b.) weld completed without use of flux maintaining the previous Arc Energy of 0.24 kJ/mm c.) full penetration weld completed without flux requiring an Arc Energy of 0.49 kJ/mm.

Transverse weld cross sections illustrating this relationship are shown in Figures 3a to 3c. Figure 3a shows a full penetration weld produced using GTAW flux and an arc energy of 0.24 kJ/mm. When welding with identical parameters, but no flux, penetration of the weld reached the mid-wall location, as shown in Figure 3b. Complete penetration without the use of flux was achieved only at a much higher arc energy of 0.49 kJ/mm demonstrated in Figure 3c. As shown in Figure 1 and Figure 3c, the use of higher arc nergies resulted in the production of a large weld pool with excessive root reinforcement. In addition to the unacceptable bead profile in welds produced without flux, higher ferrite percentages (~70 %) were recorded.

The time required to produce single-pass full penetration manual welds in the 12.7 mm (0.50 in.) diameter tube typically ranged from 15 to 20 minutes per weld. The use of flux and automatic welding equipment, together with the procedures described in this paper, decreased the weld completion time to less than 5 minutes. Improvements to these preliminary welding procedures are possible allowing for further reduction of the cycle times. As expected, the use of automatic welding equipment and the GTAW flux reduced reject rates in field application trials. Because computerized orbital GTAW welding equipment is easy to use, training and qualification for field use typically required only a few days rather than years of hands-on experience normally required for the successful production of manual welds.

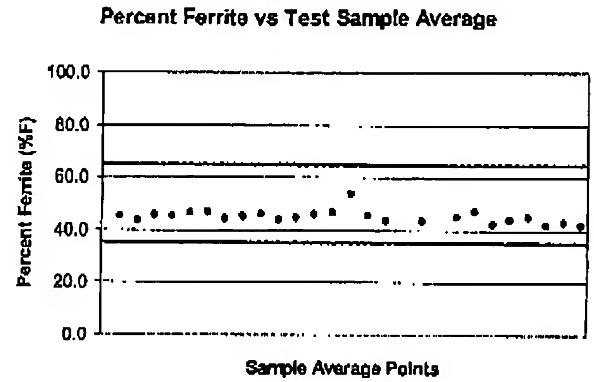

Figure 4: Average percentage of ferrite measured in test samples. Bold lines represent acceptable limits.

Customer acceptance criteria were established based on current requirements from several oil and gas companies. With the use of GTAW flux and automatic welding procedures, all acceptance criteria were met. The welding procedures developed in this project resulted in the production of welds that maintained a consistent ferrite percentage of 42 to 54 %, with the mean being 45 %. For the range of welding parameters utilized in this study, the ferrite number was essentially independent of the cooling rate, as shown in Figure 4.

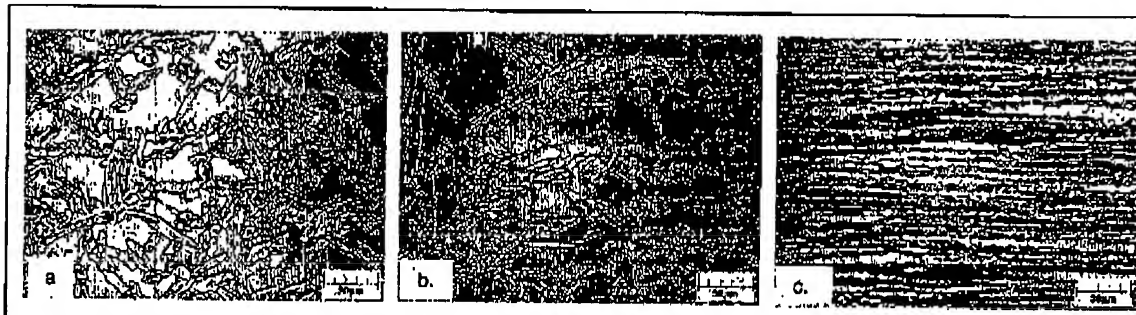

Figure 5: Representative microstructure of SAF 2507 weldments and base metal when GTAW flux was used. Images are: a.) weld metal, b.) fusion boundary, c.) base metal

Figure 5 shows representative microstructures in the SAF 2507 weld, fusion line, and base metal regions. Evaluation of ferrite measurement at three independent laboratories indicates that results produced using point counting, magnegage, and Fischer ferritscope provide similar results.

Experience with SAF 2507 and other duplex/super duplex materials suggests that it can be quite difficult to maintain adequate phase balance in conventional welds

ary investigation of microstructural evolution in

the GTAW flux welds suggests that the use of flux reduces nitrogen loss during welding, as noted in Table 4. Additional investigation regarding the effects of GTAW flux on the evolution of duplex/super duplex weld microstructure is underway.

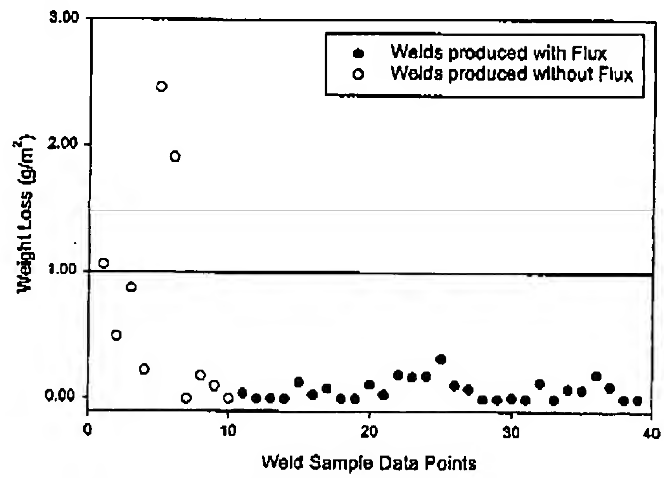

Figure 6: Averages for G-48 Method A, evaluations. Each data point represents one test coupon. Bold line represents maximum allowable weight loss.

Figure 6 summarizes the results of the corrosive weight loss tests measured in welds produced with and without the use of GTAW flux. Consistent with the maintenance of appropriate phase balance, corrosive weight loss was maintained at levels well below the specified maximum levels. Also noted in Figure 6, welds made with flux experienced significantly lower and more consistent weight loss values than those produced without the aid of flux.

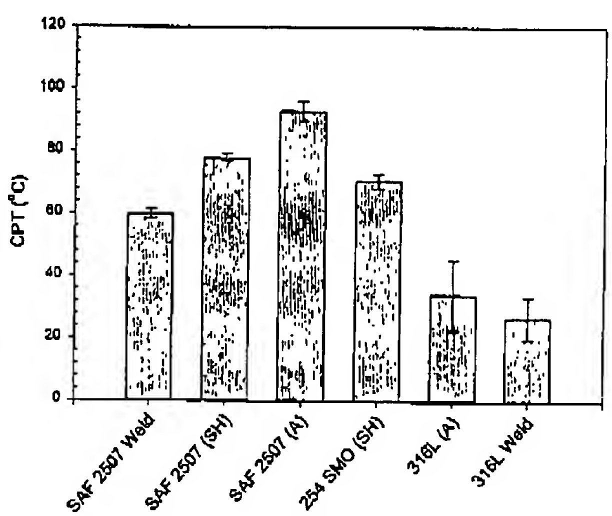

Figure 7: Preliminary G150 results, noting comparable materials and typical forms used for subsea application. A=Annealed Tubing, SH=Strain Hardened Bar, Weld=Tube to Tube Butt-Weld

Figure 7 shows electrochemical pitting temperature test (CPT) results for a range of materials typically utilized in sub-sea applications. The values denoted "SAF 2507 Weld" represent values for welds produced using GTAW flux. These results are well within the typical specifications required by oil and gas companies for sub-sea installations.

Tensile and bend properties for each size tube listed in Table 1 were evaluated in accordance with ASME Section IX (QW-462.1—tensile test procedure, QW-462.3—root and face bend procedure). Hydraulic burst tests were also completed as a secondary verification that the mechanical properties of the weldments were at or above the required levels. All coupons evaluated exceeded the minimum tensile and bend requirements and exhibited exceptional performance during burst testing. Radiographic was used to verify that the welds were free from porosity. The results for the mechanical tests and radiographic inspection can be found in Table 5. Over 1200 w lds from various field

ng the course of this inv stigation. The

results of this study indicate that the procedures developed for this t st are capable of producing consistent high quality welds.

Table 5: Mechanical tests, Hydraulic Burst Tests and Radiographic Analysis of SAF 2507 Tubing Welded Using GTAW Flux.

Requirement	Coupon Size	Results (Avg.)
Tensile Testing UTS >116 000 psi	6.35mm x 1.65mm	841 MPa (122 000 psig)
	9.53mm x 2.11mm	889 MPa (129 000 psig)
	12.7mm x 2.41mm	896 MPa (132 600 psig)
Guided bend tests No Visible Defects Face and Root Bends	6.35mm x 1.65mm	Passed
	9.53mm x 2.11mm	Passed
	12.7mm x 2.41mm	Passed
Hydraulic Burst Working pressures listed in Table 1 (≥ 1378 bar)	6.35mm x 1.65mm	5647 bar (81 900 psig)
	9.53mm x 2.11mm	4930 bar (71 500 psig)
	12.7mm x 2.41mm	4171 bar (60 500 psig)
Radiograph 2 % Sensitivity	All Sizes	Passed @ <2 % Sensitivity

CONCLUSIONS

The results of this study demonstrate that the use of GTAW flux, in conjunction with automatic welding equipment, can consistently produce high-quality welds in SAF 2507 small-bore tubing. The welds produced using the tested flux/automatic orbital welding process combination improved productivity and quality while meeting microstructure, mechanical property, and weld integrity criteria established for SAF 2507 sub-sea tubing applications. The results of this study demonstrate that:

- Weld metal ferrite content can be maintained between 42 and 52 % when using GTAW flux and automated autogenous automatic welding procedures.
- The use of GTAW flux increased penetration 250 to 300% on SAF 2507 tubing.
- The use of GTAW flux was required to maintain acceptable weld bead dimensions in the heavy wall duplex stainless steel tube.
- Preliminary evaluation of weld metal of flux welds on SAF 2507 suggests that the GTAW flux evaluated for this test encourages nitrogen preservation, without the use of nitrogen in the shielding gas or a nitrogen boosted filler.
- Substantial time savings were possible with the use of GTAW flux and automatic welding equipment; cycle time was reduced from 15 to 20 minutes for manual welding to less than 5 minutes for automatic welding with GTAW flux.

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LECO (Interstitial Analyzers)
Fischer ferritscope (digital-magnetic probe)
Magnegage (mechanical-magnetic probe calibrated for duplex microstructures)